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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Three nonlinear optical effects in (Hg,Cd)Te have been experimentally evaluated, including the spin-flip Raman laser, four-photon mixing, and optical phase conjugation. Theoretical analysis has revealed the role that Auger recombination plays in limiting the lifetime in p-type (Hg,Cd)Te and strongly degenerate n-type (Hg,Cd)Te. Diamondlike carbon thin films have been produced by argon sputtering in the presence of hydrocarbon gas. Ten major new discoveries have been documented. One patent disclosure was filed and

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*cont.*

one is in preparation. Ten scientific papers have been published, two chapters are in press and two papers have been accepted for publication. Twenty-three spoken papers have been presented at scientific meetings and four have been submitted for presentation. Twenty-six major interactions with other scientists and organizations have occurred. Samples of (Hg,Cd)Te have been supplied to six universities and institutes, and samples of diamondlike carbon thin films to one government agency.

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F49620-77-C-0028

1. RESEARCH OBJECTIVES

The objectives of the contract are listed below:

- a. Grow five crystals of  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  by the modified Bridgman (quench/anneal) method.
- b. Determine the composition and purity profiles of the crystals.
- c. Prepare spin-flip Raman laser cavities from selected sections of the crystals.
- d. Evaluate the utility of the cavities in the spin-flip Raman laser test apparatus.
- e. Measure the spatial uniformity of cavities from one crystal.
- f. Determine the optimum purity for spin-flip Raman laser operation.
- g. Evaluate the technical feasibility of a  $(\text{Hg,Cd})\text{Te}$  spin-flip Raman laser operating at 77°K.
- h. Develop insights into the properties of narrow bandgap materials which make them suitable for use in 15-30 $\mu\text{m}$  infrared detectors and which make them resistant to laser damage.
- i. Measure the spin-flip Raman spontaneous linewidth in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ .
- j. Determine the fine tuning behavior of the  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  spin-flip Raman laser.
- k. Evaluate the spatial uniformity of the transmitted spin-flip signals from a  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  cavity.
- l. Investigate tunable laser effects in  $(\text{Hg,Cd})\text{Te}$  by difference frequency generation due to spin nonlinearities.
- m. Investigate tunable laser effects in  $(\text{Hg,Cd})\text{Te}$  by resonant four-photon mixing.
- n. Calculate the dependence of the Auger lifetime on temperature, carrier concentration, and alloy composition for transitions involving only the conduction and heavy hole bands.
- o. Determine effects of the light hold band in semiconductors such as  $(\text{Hg,Cd})\text{Te}$  on Auger recombination in p-type material.
- p. Elucidate effects of degenerate statistics on the Auger lifetime in semiconductors such as  $(\text{Hg,Cd})\text{Te}$ .

- q. Automate the measurement of the spatial uniformity of the  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  spin-flip Raman laser measurements using a computer-driven scanning galvanometer light beam deflector.
- r. Investigate theoretically and experimentally the dependence of 4-photon mixing output power upon input power from the two  $\text{CO}_2$  lasers.
- s. Determine the dependence of output frequency upon magnetic field for difference frequency generation in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ .
- t. Determine the conversion efficiency of difference frequency generation in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  as a function of magnetic field and  $\text{CO}_2$  input power.
- u. Determine the usefulness of the spin-flip Raman laser nonlinearity in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  for optical phase conjugation.
- v. Calculate the Auger lifetime for  $(\text{Hg},\text{Cd})\text{Te}$  as a function of temperature, composition and carrier concentration for highly degenerate (approx.  $5 \times 10^{16} - 10^{19} \text{ cm}^{-3}$ ) material.
- w. Design infrared detector concepts based on the results of the theoretical prediction of the Auger lifetime, for degenerate statistics and with inclusion of the conduction band-light hole band transition.
- x. Compare the theory of the mobility in n-type  $(\text{Hg},\text{Cd})\text{Te}$  with experiment in order to explore the variability of the mobility in  $(\text{Hg},\text{Cd})\text{Te}$  samples having identical carrier concentrations and x values.
- y. Study the parameters involved in the plasma arc ion beam deposition of "diamondlike" carbon thin films.
- z. Establish correlations between composition, method of growth, and physical properties of carbon thin films.

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## 2.0 SUMMARY OF SIGNIFICANT ACCOMPLISHMENTS

Listed below are the significant accomplishments achieved during the period 1 January 1977 - 31 December 1980, organized according to research objectives:

- a. Objective: Grow five crystals of  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  by the modified Bridgman (quench/anneal) method.

Accomplishment: Five crystals of n-type  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  were prepared to our specifications by the Honeywell Electro-Optics Center, and delivered to the Honeywell Corporate Technology Center. The samples were prepared by the modified Bridgman (quench/anneal) method and were provided by Honeywell at no cost to the contract. Properties of the samples are summarized in the table below.

Sample Number	Electron Concentration	Average x
20177	$1.8 \times 10^{15} \text{cm}^{-3}$	0.248
30577	$1.8 \times 10^{16} \text{cm}^{-3}$	0.230
30478	$1.5 \times 10^{16} \text{cm}^{-3}$	0.220
40978	$8.0 \times 10^{15} \text{cm}^{-3}$	0.234
41178	$2.0 \times 10^{15} \text{cm}^{-3}$	0.234

- b. Objective: Determine the composition and purity profiles of the crystals.

Accomplishment: The samples were in the form of ingots 12.7mm diameter x 130mm long. They were characterized by cutting 1mm thick slices from positions spaced about 20mm apart along the length of the samples. The slices were sectioned into 6 vertical sections. For each such section the composition (x value) was obtained by weighing the section in air and in oil to obtain the density. The carrier concentration (purity) was determined by 4 point probe measurements of electrical resistivity and Hall mobility at 77K. These results yielded the profile of the composition and carrier concentration as a function of position through the ingots.

- c. Objective: Prepare spin-flip Raman laser cavities from selected sections of the crystals.

Accomplishment: Using the results of the compositional analysis to select regions of the ingots for which  $x = 0.23$ , the composition for which the band edge of the material corresponds to the wavelength of the  $\text{CO}_2$  laser, regions of the ingots were fabricated into laser cavities. The ingots were cut with a wire saw. The ends of the samples were polished flat and parallel, to within 20 arc seconds, on a conventional lapping fixture. The laser cavities were 12.7mm in diameter, and ranged from 2.8 to 5mm in length (the dimension perpendicular to the polished ends). Cavities were fabricated from the above five crystals, and also from crystal 20275, grown by Honeywell before the start of the contract. Crystal 20275 was n-type with a carrier concentration of  $1.1 \times 10^{15} \text{cm}^{-3}$ .

- d. Objective: Evaluate the utility of the cavities in the spin-flip Raman laser test apparatus.

Accomplishment: In the test apparatus, radiation from the Q-switched CO<sub>2</sub> pump laser was focused on the input face of the cavity. The spin-flip output was focused onto the input of a grating spectrometer, the output of which was detected by a photovoltaic Hg<sub>0.80</sub>Cd<sub>0.20</sub>Te infrared detector followed by an amplifier and boxcar integrator. The cavity was mounted in a liquid helium dewar, between the pole faces of an electromagnet. In the initial experiments, the cavity was on a cold finger in contact with the helium. Later, in a modified design, the cavity was immersed in liquid helium.

Spin-flip Raman laser operation was demonstrated under a variety of conditions, including variable pump wavelength (9.6, 10.3 and 10.6  $\mu$ m) and variable magnetic field up to 13 kG. Both Stokes and anti-Stokes lines were observed.

The tuning of the first Stokes and anti-Stokes lines with magnetic field was found to be 3.8 cm<sup>-1</sup>/kG.

Second Stokes lines were present under some conditions. The second Stokes lines, arising from Raman scattering of the first Stokes lines, tune with field at twice the rate of the first Stokes lines. With proper choice of pump wavelength and magnetic field, an output could be obtained at any wavelength between 9.6 and 11.2  $\mu$ m.

One of the principal accomplishments was the demonstration that a high external conversion efficiency can be obtained from a Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te spin-flip Raman laser. The efficiency was determined by measuring the power of the CO<sub>2</sub> laser, the signal from the infrared detector, and the throughput of the spectrometer. According to convention, the external conversion efficiency is twice the detected output power divided by the input power, the factor of two arising because half the radiation is emitted from each face of the sample.

The external conversion efficiency was found to have a maximum value of 9% at magnetic fields of approximately 2 kG and 7 kG. Because of reflection losses suffered by both the CO<sub>2</sub> pump radiation and the spin-flip Raman radiation, the measured external conversion efficiency of 9% corresponds to an internal conversion efficiency of approximately 50%. Thus the data show that the pump radiation is converted to stimulated Raman radiation with a very high efficiency. This is confirmed by observation of pump depletion, i.e., the transmitted CO<sub>2</sub> pump radiation was reduced in intensity due to conversion by the spin-flip process.

The first time-resolved data for a Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te spin-flip Raman laser were obtained. By comparing the transmitted pump pulse with and without the field, clear evidence of pump depletion was obtained. In general the spin-flip pulse duration was determined

to be shorter than that of the pump pulse. Measurements of the pump pulse power density at  $0.4 \text{ MW/cm}^2$  showed that not only is the pump pulse depleted, but also a "notch" appears in the spin-flip pulse. This is attributed to highly efficient conversion of first Stokes radiation to anti-Stokes and second Stokes, causing depletion of the first Stokes pulse.

- e. Objective: Measure the spatial uniformity of cavities from one crystal.

Accomplishment: The spatial uniformity of 5 mm thick cavities from crystal 20275 was determined from transmission measurements. The samples were moved by micrometer drives through a  $\text{CO}_2$  laser beam. The amplitude of the transmitted beam was plotted on an x-y recorder, with the x-position synchronized with the horizontal motion of the sample. In this way profile maps of the transmission were obtained. These measurements were carried out at sample temperatures of 12K, 77K and 300K. The transmission showed wide variation as a function of position. Small regions with dimensions of a few millimeters exhibited transmission much higher than the average. Regions of high transmission were found to be correlated, although not perfectly, with regions of high laser efficiency. It would be tempting to ascribe the variations in transmission to compositional variations, which would shift the band edge slightly. However, the same pattern of transmission variability was observed at 12K, 77K and 300K. At 300K, the band edge has moved to about  $7 \mu\text{m}$ . Small changes in composition could not account for the spatial variation of the  $10 \mu\text{m}$  transmission at 300K. The cause of the nonuniformity of the transmission and its relation to the efficiency of the spin-flip laser operation was not determined.

- f. Objective: Determine the optimum purity for spin-flip Raman laser operation.

Accomplishment: Samples with electron concentrations which varied from  $1.1 \times 10^{15}$  to  $1.8 \times 10^{16} \text{ cm}^{-3}$  were employed. Spin-flip Raman laser operation was obtained from samples which had carrier concentrations in the range  $(1-2) \times 10^{15} \text{ cm}^{-3}$ , but not from the samples with carrier concentrations in the range near  $10^{16} \text{ cm}^{-3}$ .

In particular, despite considerable effort, spin-flip Raman laser operation was not obtained from a cavity from the heavily doped crystal 30577, having a carrier concentration of  $1.8 \times 10^{16} \text{ cm}^{-3}$ . Calculations indicate that the upper spin state of the  $N = 0$  Landau level should not emerge above the Fermi level until a field of 33 kG is reached, a value which cannot be achieved by Honeywell. Although operation on other Landau levels should be possible below our maximum field of 13.5 kG, laser operation was not obtained from this sample.

The determination of optimum carrier concentration is complicated by the spatial nonuniformity of the samples, and by the fact that laser emission occurs with high efficiency only from a few small regions in a sample. Within these limitations, it can be concluded that with reasonable magnetic fields ( $\leq 13$  kG), the optimum carrier concentration is about  $(1-2) \times 10^{15} \text{ cm}^{-3}$ .

- g. Objective: Evaluate the technical feasibility of a (Hg,Cd)Te spin-flip Raman laser operating at 77K.

Accomplishment: A theoretical analysis of the dependence of the threshold for spin-flip Raman laser operation on carrier concentration, temperature and magnetic field, was carried out. The results indicated there is no fundamental reason prohibiting spin-flip Raman laser operation at 77 K, provided that the magnetic field is sufficiently high.

Crystal 30478 was prepared with an x value of 0.22, which is the composition for which the energy bandgap at 77 K corresponds to the energy of a CO<sub>2</sub> pump laser photon. However, spin-flip Raman laser operation at 77 K was not obtained with this sample. The analysis indicated that for the carrier concentration of  $1.5 \times 10^{16} \text{ cm}^{-3}$  in 30478, the magnetic field at threshold should exceed 20 kG. Because the maximum field of the magnet was 13 kG, the experimental results were inconclusive.

- h. Objective: Develop insights into the properties of narrow bandgap materials which make them suitable for use in 15-30 $\mu\text{m}$  infrared detectors and which make them resistant to laser damage.

Accomplishment: The work in this contract has led to clearer insights into the properties of mercury cadmium telluride as a material for nonlinear optics. It also has relevance for understanding the properties of narrow bandgap materials which make them suitable for use in 15-30 $\mu\text{m}$  infrared detectors and which make them resistant to laser damage.

Hg<sub>1-x</sub>Cd<sub>x</sub>Te is a suitable candidate material for use in 15-30 $\mu\text{m}$  infrared detectors. The x-value lies between x=0.205, which gives peak response at 12 $\mu\text{m}$  at 77K and 16 $\mu\text{m}$  at 4K; and x=0.17, the value at which the material becomes semimetallic. The operating temperature will be less than 77K in order to attain background limited performance. N-type material will be superior to p-type.

Laser damage has been observed in our spin-flip Raman laser cavities. The damage occurs when the intensity of the CO<sub>2</sub> laser pump exceeds a threshold value about  $10^6 \text{ W/cm}^2$  peak. Although the damage mechanism specific to Hg<sub>1-x</sub>Cd<sub>x</sub>Te was not established, it is likely that it involves a thermal mechanism at least in part. Absorption of radiation near 10.6 $\mu\text{m}$  causes heating, increased



carrier concentration and eventually, catastrophic thermal runaway. The observation that increased transmission accompanies high levels of Raman laser signal may offer a possible new means of evaluating material for infrared detectors.

- i. Objective: Measure the spin-flip Raman spontaneous linewidth in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ .

Accomplishment: The spontaneous linewidth of a  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  spin-flip Raman laser was measured for the first time by Honeywell under the contract. At low magnetic fields, such that emission is spontaneous rather than stimulated, emission lines appear at approximately 360, 720 and 1080 G. As the magnetic field is raised from zero while the  $\text{CO}_2$  laser is pumping the sample, weak spontaneous emission occurs which is undetectable. The frequency of this radiation is shifted from the pump frequency at a rate of  $3.8 \text{ cm}^{-1}/\text{kG}$ . Because the Q-switched  $\text{CO}_2$  laser emits not only the principal line but also weak satellite lines separated from the main one by approximately  $1.35 \text{ cm}^{-1}$ , when the magnetic field reaches approximately 360 G, the spontaneous emission has been shifted  $1.35 \text{ cm}^{-1}$ , thereby bringing it into coincidence with a satellite pump line. These lines mix in the infrared detector, which thus operates in a heterodyne mode, at a very high sensitivity. Each of the lines is in reality split into several lines. The width of each (FWHM) is approximately 8 G, or  $0.03 \text{ cm}^{-1}$ . If all of this width were attributed to nonuniformities in composition throughout the volume being pumped (a cylinder 0.25 mm diameter x 5 mm long), then calculations show that the composition variable  $x$  is uniform within that region to less than 0.001. Since the average value of  $x$  is 0.23, this means that the sample is uniform in composition throughout the volume pumped to 1 part in 230, or about 0.5%. This is a new and novel method for determining the upper limit to the compositional nonuniformity of  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ .

Several spontaneous, closely spaced lines are observed at selected fields. This is attributed to conduction band non-parabolicity. At the operating temperature of approximately 10 K, the free electrons lie within 1 meV about the Fermi level, which lies about 4 meV above the band edge. This means that several of the upper Landau levels are occupied at fields of less than, say, 1500 G. Because of the nonparabolicity of the conduction band, the spin level splitting factor ( $g$ -value) decreases with increasing energy above the band edge. Therefore the dependence of spontaneous emission frequency with magnetic field is multiple valued at low fields, giving rise to more than a single emission line at the fields where the spin-flip emission frequency coincides with a pump laser satellite line frequency. Observation of nonparabolicity by this means had never been previously reported for a spin-flip Raman laser, either  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  or InSb.

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Longitudinal cavity mode structure has been reported in InSb spin-flip Raman lasers but never for a  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  one. We obtained clear evidence of cavity modes at low fields, confirming that the spontaneous linewidth at low fields is less than the cavity mode spacing. Since the linewidth at 720 G is 8 G and the cavity mode spacing is 71 G, this is expected. It is not possible to measure directly the spontaneous linewidth at high fields, say 8kG, because the emission is stimulated. Still, the fact that the cavity mode structure disappears at these high fields is clear evidence that the spontaneous linewidth increases with increasing field. Similar effects are observed in high purity InSb. Therefore, it can be concluded that the spontaneous linewidth at these high fields exceeds 71 G: it may be proportional to field.

- j. Objective: Determine the fine tuning behavior of the  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  spin-flip Raman Laser.

Accomplishment: The fine tuning characteristics of the spin-flip Raman laser were determined by means of a Fabry-Perot interferometer. No evidence of mode hopping was found, even when the pump laser power was reduced to near threshold. Continuous tuning without mode hopping has also been observed in InSb spin-flip Raman lasers under some conditions. It is a desirable attribute for most applications, e.g., spectroscopy.

From the fine tuning characteristics, the spin-flip Raman laser stimulated linewidth was calculated as a function of magnetic field. The linewidth was found to increase smoothly with magnetic field from  $0.1 \text{ cm}^{-1}$  at 2kG to  $0.6 \text{ cm}^{-1}$  at 8 kG. The extremely narrow linewidths reported by other workers for the InSb spin-flip Raman laser operated CW were not observed. This is believed due to the fact that our studies were in the pulsed mode, and that compositional uniformity also contributed to the line broadening. This is the first measurement of the spin-flip Raman laser stimulated linewidth in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ .

- k. Objective: Evaluate the spatial uniformity of the transmitted spin-flip signals from a  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  cavity.

Accomplishment: The spatial uniformity of the spin-flip Raman laser emission has been evaluated for cavities from two ingots: 20177 and 20275. The sample was moved by micrometer drives so that the pump beam was incident upon different regions of the cavity, and the intensity of the emission was mapped as a function of spatial position. The results were very similar for different cavities and for cavities made from the two different crystals, ensuring that the observed characteristics were not artifacts associated with a particular sample of material. The spatial uniformity is marked by "sweet spots" with relatively high efficiency and with dimensions of the order of several millimeters.

When the sample is mounted on the cold finger in the liquid helium dewar, its temperature is around 12 K. In that case, emission occurs from only a few spots in the cavity. With the sample immersed in liquid helium at 2 K, spatial variations in the spin-flip laser output are reduced from what was observed at 12 K. A larger portion of the sample contributes to the spin-flip Raman laser operation.

1. Objective: Investigate tunable laser effects in (Hg,Cd)Te by difference frequency generation due to spin nonlinearities.

Accomplishment: Attempts were made with the collaboration of the M.I.T. nonlinear optics group to observe the difference frequency signal at frequency  $(\omega_1 - \omega_2)$  using the spin nonlinearity. These experiments were partially successful. Samples of  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  were pumped simultaneously by two  $\text{CO}_2$  laser beams at frequencies  $\omega_1$  and  $\omega_2$ . Both beams were focussed on the same spot on the sample to a spot size of 2 mm diameter. The beam powers were approximately  $1 \text{ kW/cm}^2$  each. The frequencies  $\omega_1$  and  $\omega_2$  were selected such that  $\Delta\omega = \omega_1 - \omega_2$  ranged from  $\sim 40 \text{ cm}^{-1}$  to  $120 \text{ cm}^{-1}$ . Signals were observed at  $\omega_4 = 2\omega_2 - \omega_1$  for all the different frequency combinations used, but the signals at frequencies  $\Delta\omega$  could not be observed due to the low sensitivity of the detector at long wavelengths.

- m. Objective: Investigate tunable laser effects in (Hg,Cd)Te by resonant four-photon mixing.

Accomplishment: Investigations of resonant four-photon mixing in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  resulted in several significant results, including the first reported determination of the following:

- first observation in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$
- first report of 6-photon mixing in any solid
- first determination of the resonant third order nonlinear susceptibility of  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ .

In the studies of four-photon mixing, the radiation from 2  $\text{CO}_2$  pump lasers at angular frequencies  $\omega_1$  and  $\omega_2$  (where  $\omega_1 > \omega_2$ ) was combined to produce radiation at frequency  $\omega_3 = 2\omega_1 - \omega_2$  and  $\omega_4 = 2\omega_2 - \omega_1$  via a resonant 4-photon mixing process involving the spin nonlinearity. In addition resonant 6-photon mixing at frequency  $3\omega_2 - 2\omega_1$  was observed.

For this portion of the work, the configuration was different from that of the spin-flip Raman laser experiments. The sample was mounted in a liquid helium dewar. During the first measurements of four-photon mixing, the sample was mounted on a cold finger at 12 K. Later, the sample was immersed in liquid helium at 2 K. The dewar was mounted between the pole faces of an

electromagnet. Unlike the spin-flip Raman laser experiments, which used one CO<sub>2</sub> pump laser, the sample was pumped by two Q-switched CO<sub>2</sub> lasers, which emitted pulses of 200 nsec duration and peak power of 1 kW. The two pump laser beams were combined with a beam splitter and focused on the sample collinearly by a lens of 250 mm focal length. The pulses from the two pump lasers were synchronized by Q-switching both lasers with the same rotating two-faced mirror. Both pump lasers were separately line tunable with individual diffraction gratings. The output signals at  $\omega_3$  and  $\omega_4$  were distinguished from the transmitted pump laser radiation by a monochromator, and were monitored by a Hg<sub>0.80</sub>Cd<sub>0.20</sub>Te infrared detector. The output of the detector was summed by a gated integrator, the output of which was fed into the y-axis of an x-y recorder.

Recorder traces with magnetic field used as the input to the x-axis were obtained. The magnetic field was scanned by the signal from a function generator which was input to the electro-magnet power supply. A magnetic field sensor drove the x-axis of the recorder. A strong resonance was observed at  $\omega_3$  and  $\omega_4$  when the magnetic field satisfied the condition  $|\omega_1 - \omega_2| = g\mu H$ , where  $g$  is the spin-level splitting factor for Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te,  $\mu$  is the Bohr magneton, and  $H$  is the magnetic field.

The original measurements were carried out with collinear pump beams. In this configuration, refractive index dispersion caused the beams not to be phase matched within the Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te sample. Resonant noncollinear phase matched four-photon mixing was also investigated. In these experiments the angle between the incident beams at  $\omega_1$  and  $\omega_2$  was varied to determine the optimum phase-matching angle, which was found to be 2.5°, in very close agreement with theory.

When the two pump beams were offset at this optimum angle, the amplitude of the four-photon signal increased by a factor of 10 compared with the collinear case.

Under some conditions a smaller resonant 6-photon mixing signal at frequency  $3\omega_2 - 2\omega_1$  was observed. Six-photon mixing is also a resonant process, displaying a sharp maximum when the magnetic field  $H$  satisfies the condition  $|\omega_1 - \omega_2| = g\mu H$ .

A resonant mixing of two pump frequencies  $\omega_1$  and  $\omega_2$  to produce  $\omega_6 = 3\omega_2 - 2\omega_1$  had previously been demonstrated in liquids by other workers. This is the first demonstration of such mixing in a solid material.

From measurements of the efficiency of four-photon mixing, and from measurements of the threshold for spin-flip Raman laser operation, the calculated resonant third order nonlinear susceptibility of Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te was found to be  $1-3 \times 10^{-4}$  esu. This is the highest value ever reported for any material, and is about 10 times higher than for InSb.

- n. Objective: Calculate the dependence of the Auger lifetime on temperature, carrier concentration, and alloy composition for transitions involving only the conduction and heavy hole bands.

Accomplishment: A software program was developed which allowed the Auger 1 lifetime to be quickly calculated and plotted as a function of temperature, carrier concentration, and alloy composition.

- o. Objective: Determine effects of the light hole band in semiconductors such as (Hg,Cd)Te on Auger recombination in p-type material.

Accomplishment: There are two major Auger recombination mechanisms, Auger 1 and Auger 7. In order to determine their relative importance, as well as their importance with respect to other recombination mechanisms, it was necessary to develop a consistent calculation at the associated lifetimes.

This was done for the first time under this contract for the non-degenerate case. It was shown that in defect-free material Auger 7 is the lifetime limiting mechanism in p-type (Hg,Cd)Te for hole concentrations greater than or equal to  $10^{15} \text{ cm}^{-3}$  and temperatures below 100 K. This result reverses a previously held belief that radiative recombination was the dominant lifetime limiting mechanism in the 8 - 14  $\mu\text{m}$  region. In addition, it was shown that for intrinsic material Auger 1 and Auger 7 contribute almost equally to the Auger lifetime. This then clarifies the symmetry between Auger 1 and Auger 7 with Auger 1 being the dominant Auger mechanism in n-type (Hg,Cd)Te.

- p. Objective: Elucidate effects of degenerate statistics on the lifetime in semiconductors such as (Hg,Cd)Te.

Accomplishment: The lifetime mechanisms in degenerate, n-type narrow bandgap semiconductors such as (Hg,Cd)Te involve regions of the conduction band where a parabolic band approximation is not valid. In fact, even an approximate non-parabolic band is unacceptable. This was resolved by developing a more realistic and accurate conduction band which is based on the original Kane k.p bandstructure but with additional parameters found by Weiler from magneto optical experiments.

With this more valid band structure the position of the Fermi level can be determined as a function of the electron concentration. It was found that for a given electron concentration, (Hg,Cd)Te is not as degenerate as is predicted, using the more approximate band structure.

- q. Objective: Automate the measurement of the spatial uniformity of the  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  spin-flip Raman laser measurements using a computer-driven scanning galvanometer light beam deflector.

Accomplishment: A system for characterizing the (Hg,Cd)Te samples, employing a computer-driven galvanometer flying spot scanner and computerized data acquisition capability, was constructed. It incorporated software which automatically plots the four-photon mixing signal at  $\omega_4$  at a particular field when an area of 3 x 3 mm is scanned with a 100x100 matrix in only 6 minutes.

The experimental arrangement uses two  $\text{CO}_2$  lasers at frequencies  $\omega_1 = 975 \text{ cm}^{-1}$  and  $\omega_2 = 945 \text{ cm}^{-1}$ . These collinear beams are focussed onto the (Hg,Cd)Te wafer inside a liquid He dewar placed between the pole faces of an electromagnet. The scanner moves the collinear focussed beams across the sample in a raster. Signals are detected using a helium cooled Cu(Ge) detector, amplified, and fed to a boxcar integrator. The boxcar signal is then sent to PDP-11 minicomputer and is stored on a disc. The signals can be plotted in a 3-D plot. The transmission of the two lasers over the sample face can also be displayed in a 3-D plot. The software allows a plot of contours of equal signal intensity over the crystal face.

- r. Objective: Investigate theoretically and experimentally the dependence of four-photon mixing output power upon input power from the two  $\text{CO}_2$  lasers.

Accomplishment: Theoretically, the four-photon output power  $P_4$  at frequency  $\omega_4 = 2\omega_2 - \omega_1$ , is expected to be:

$$P_4 = \frac{256\pi^4 \omega_4^2 P_2^2 P_1^2 \chi^{(3)2} L^2}{n^4 c^4 A^2}$$

where  $P_2$  and  $P_1$  are the input powers at  $\omega_2$  and  $\omega_1$  respectively,  $\chi^{(3)}$  is the resonant third-order nonlinear susceptibility of  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ ,  $n$  is the index of refraction,  $c$  is the velocity of light,  $A$  is the cross sectional area in which the beams interact and  $L$  is the coherence length for the interaction.

The dependence of  $P_4$  on  $P_2$  (with  $P_1$  constant) and on  $P_1$  (with  $P_2$  constant) was measured. The power  $P_4$  was found to increase quadratically with  $P_2$ , and linearly with  $P_1$ . These results are in agreement with the theoretical prediction.

- s. Objective: Determine the dependence of output frequency upon magnetic field for difference frequency generation in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ .

Accomplishment: Due to the failure to observe difference frequency signals (see Objective 1), this objective was not achieved.

- t. Objective: Determine the conversion efficiency of difference frequency generation in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  as a function of magnetic field and  $\text{CO}_2$  input power.

Accomplishment: Due to the failure to observe difference frequency signals (see Objective 1), this objective was not achieved.

- u. Objective: Determine the usefulness of the spin-flip Raman laser nonlinearity in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  for optical phase conjugation.

Accomplishment: Optical phase conjugation in  $(\text{Hg},\text{Cd})\text{Te}$  was demonstrated for the first time. Both degenerate and resonant four-wave mixing experiments were carried out. The degenerate four-wave mixing experiments were successful in both the reflective and forward modes. In the reflective mode degenerate four-wave mixing, two counterpropagating pump beams and a probe beam were incident upon the sample of  $(\text{Hg},\text{Cd})\text{Te}$ . The phase conjugate signal was reflected from the sample back up the probe beam. In the forward mode experiments, the phase conjugate signal emerged from the side of the sample opposite to that on which the pump and probe beams were incident. The phase conjugate signals were studied as a function of x-value, temperature, and carrier concentration. The data were fitted to a theoretical model in which conduction band nonparabolicity was responsible for the third order nonlinear susceptibility  $\chi^{(3)}$ .

Optical phase conjugation experiments based upon resonant four-wave mixing were successfully carried out in the forward direction. Radiation from two Q-switched  $\text{CO}_2$  lasers operating at  $\omega_1$  and  $\omega_2$  were incident on the same side of a sample of  $(\text{Hg},\text{Cd})\text{Te}$ , which was in an optical dewar in a magnetic field. In order to phase match, the beams were at a small angle ( $\sim 2.5^\circ$ ) with respect to each other. Phase conjugate signals observed at  $\omega_3 = 2\omega_1 - \omega_2$  and  $\omega_4 = 2\omega_2 - \omega_1$  were detected in the forward direction. The data were fitted to a model based upon spin resonance of the conduction electrons.

This is the first time that optical phase conjugation by any means has been observed in  $(\text{Hg},\text{Cd})\text{Te}$ .

- v. Objective: Calculate the Auger lifetime for  $(\text{Hg},\text{Cd})\text{Te}$  as a function of temperature, composition and carrier concentration for highly degenerate (approximately  $5 \times 10^{16} - 10^{19} \text{ cm}^{-3}$ ) material.

Accomplishment: For the first time the Auger 1 lifetime ( $\tau_{A1}^D$ ) in highly degenerate n-type  $(\text{Hg},\text{Cd})\text{Te}$  has been calculated as a function of carrier concentration. Since degenerate Auger 1 has roughly the same  $n_0$  dependence as radiative recombination, these two mechanisms will compete to limit the lifetime in highly degenerate, n-type  $(\text{Hg},\text{Cd})\text{Te}$ .



- w. Objective: Design infrared detector concepts based on the results of the theoretical prediction of the Auger lifetime, for degenerate statistics and with the inclusion of the conduction band-light hole band transition.

Accomplishment: This objective was not met.

- x. Objective: Compare the theory of the mobility in n-type (Hg,Cd)Te with experiment in order to explore the variability of the mobility in (Hg,Cd)Te samples having identical carrier concentrations and x values.

Accomplishment: This objective was not met.

- y. Objective: Study the parameters involved in the plasma arc ion beam deposition of "diamondlike" carbon thin films.

Accomplishment: It was found that the ion energy must be kept below 150 eV and that some residual hydrocarbon (amount undetermined) is necessary to produce diamondlike carbon thin films. The residual hydrocarbon background present in a diffusion-pumped system is necessary for the nucleation of the carbon film. In order to make films in ultrahigh vacuum it was necessary to mix a hydrocarbon gas with the argon sputtering gas in the discharge. This was unexpected; it had not been discussed by anyone else who has made these films. This requirement of a hydrocarbon "catalyst" is perhaps not surprising since metal catalysts are required for the formation of synthetic diamonds by the well-known high temperature, high pressure, graphite-to-diamond processes developed by General Electric Company. Because of the significance of this discovery, a patent disclosure is in preparation.

- z. Objective: Establish correlations between composition, method of growth, and physical properties of carbon thin films.

Accomplishment: Electron spectroscopies (ESCA, Auger, electron energy loss, photoelectric yield) showed that the carbon thin films exhibit characteristics different from graphite. These characteristics cannot be definitively interpreted as amorphous carbon or diamond and thus cannot be quantified by these techniques. However, transmission electron microscopy (TEM) has been the best technique to correlate physical properties.

TEM showed that the degree of crystallinity in the films could be increased by annealing the films at 200 C. In addition to ion beam films, both single-crystal and polycrystalline diffraction patterns were obtained from thin films deposited by decomposition of hydrocarbon gases. Single crystals of orientations 100, 110 and 111 have been detected. Diffraction

spots of these crystals index as simple cubic with lattice parameters of  $\frac{\sqrt{3}}{2} a_0$ ,  $\sqrt{3} a_0$ , and  $2 a_0$ , where  $a_0$  ( $=3.57 \text{ \AA}$ ) is the lattice parameter of diamond. This is indicative of the presence of superlattices in these films.

### 3. WRITTEN PUBLICATIONS IN TECHNICAL JOURNALS

Ten papers have been published during the period 1 January 1977 - 31 December 1980. They are:

P. Norton and P. W. Kruse, "High Conversion Efficiency  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  Spin-Flip Raman Lasers," Optics Comm. 22, 147(1977).

Paul W. Kruse, Paul Norton, and John F. Ready, " $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  Spin-Flip Raman Lasers", Proceedings of the Technical Program, Electro-Optics/Laser 78 Conference.

M. A. Khan, P. W. Kruse, and J. F. Ready, "Resonant 4-Photon and Higher Order Mixing in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ ", Optics Comm. 28, 374(1979).

Paul W. Kruse, John F. Ready, and Muhammad D. Khan, "Nonlinear Optical Effects in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ", Infra. Phys. 19, 497(1979).

Paul W. Kruse and John F. Ready, "Nonlinear Optical Effects in  $(\text{Hg},\text{Cd})\text{Te}$ ", Proceedings of Meeting of IRIS Specialty Group on Infrared Detectors, 12, 13 June, 1979, IRIA, October 1979, Volume I, p. 71.

T. N. Casselman and P. E. Petersen, "On the Dominant Auger Mechanism in P-Type  $(\text{Hg},\text{Cd})\text{Te}$ ", Proceedings of the Meeting of IRIS Specialty Group on Infrared Detectors, 12, 13 June 1979, IRIA, October 1979, Volume I, p. 37.

M. A. Khan, P. W. Kruse, and J. F. Ready, "Optical Phase Conjugation in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ", Optics Lett. 5, 261(1980).

T. N. Casselman and P. E. Petersen, "A Comparison of the Dominant Auger Transitions in p-Type  $(\text{Hg},\text{Cd})\text{Te}$ ", Solid State Commun. 33, 615(1980).

T. J. Moravec, "Color Chart for Diamondlike Carbon Films on Silicon", Thin Solid Films 70, No. 1, pp L9-L10 (1980).

M. A. Khan, T. J. Bogart, P. W. Kruse, and J. F. Ready, "Noncollinear Phase Matched Four-Photon Mixing in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ ", Optics Lett. 5, 469 (1980).

Two chapters are in press:

P. W. Kruse and J. F. Ready, "Nonlinear Optical Effects in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ", in "Mercury Cadmium Telluride", Volume 16 of Semiconductors and Semimetals, edited by R. K. Willardson and A. C. Beer, Academic Press, New York.

P. E. Petersen. Auger Recombination in  $(\text{Hg,Cd})\text{Te}$ ", in "Mercury Cadmium Telluride", Volume 18 of Semiconductors and Semimetals, edited by R. K. Willardson and A. C. Beer, Academic Press, New York.

Two papers have been accepted for publication:

T. J. Moravec and T. W. Orent, "Electron Spectroscopy of Ion Beam and Hydrocarbon Plasma Generated Diamondlike Carbon Films," J. Vac. Sci. Technol., March/April 1981.

T. N. Casselman, "Calculation of the Auger Lifetime in p-Type  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ," J. Appl. Phys., January 1981.

One paper has been submitted for publication but not yet accepted.

T. N. Casselman and P. E. Petersen, "Calculation of the Carrier Concentration Dependence of the Auger Lifetime in Degenerate n-Type  $(\text{Hg,Cd})\text{Te}$ ," submitted to Solid State Comm.

It is intended to submit the following papers subsequent to 31 December 1980, based upon research carried out during the period 1 January 1977 - 31 December 1980.

M. A. Khan, R. Bennet, and P. W. Kruse, "Generation of a Phase Conjugate Wave in the Forward Direction in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ".

H. Vora and T. J. Moravec, "Structural Investigations of Thin Films of i-C (Diamondlike) Carbon", to be submitted to Journal of Applied Physics.

T. N. Casselman, "Calculation of the Auger Lifetime in Degenerate n-Type  $(\text{Hg,Cd})\text{Te}$ ".

4. PROFESSIONAL PERSONNEL ASSOCIATED WITH RESEARCH EFFORT

The following personnel with B.S. or higher degrees participated in the research effort during the period 1 January 1977 - 31 December 1980:

Dr. Paul W. Kruse, Principal Research Fellow, Principal Investigator  
Dr. Paul Norton, Principal Research Scientist  
Mr. John F. Ready, Staff Scientist  
Dr. Muhammad A. Khan, Principal Research Scientist  
Dr. Thomas J. Moravec, Senior Principal Research Scientist  
Dr. Harshadril Vora, Principal Research Scientist  
Mr. Thomas N. Casselman, Senior Principal Research Scientist  
Dr. Paul E. Petersen, Staff Scientist  
Mr. Ronald J. Ezuck, Graduate Assistant  
Mr. David Adkins, Student Aide

## 5. INTERACTIONS

### 5.1 Spoken Papers Presented at Meetings

Twenty- three papers were presented at scientific meetings during the period 1 January 1977 - 31 December 1980.

P. Norton and P. W. Kruse, "Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te Spin-Flip Raman Laser Investigations", Bull. Amer. Phys. Soc. 22, No. 3, 435 (March 1977). Presented at the March, 1977 Meeting of the American Physical Society.

P. W. Kruse, P. Norton, and J. F. Ready, "Spatial Variation of Spin-Flip Raman Laser Emission from Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te", presented at the 1977 Annual Meeting of the Optical Society of American, Toronto, Ontario, Canada, October 10-14, 1977.

P. Norton, "Tunable Infrared Radiation from Spin-Flip Raman Lasers", presented at Air Force Institute of Technology, Dayton, Ohio, September, 1977.

W. Walukiewicz, J. H. M. Stoelinga, R. L. Aggarwal, B. Lax and P. W. Kruse, "Near Resonance Stimulated Spin-Flip Scattering in Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te", presented at the International Meeting on Semimetals and Small Gap Semiconductors, Warsaw, Poland, September 12-15, 1977. This paper was the result of scientific collaboration between Honeywell and MIT.

W. Walukiewicz, J. H. M. Stoelinga, R. L. Aggarwal, and P. W. Kruse, "Stimulated Spin-Flip Raman Scattering in Hg<sub>1-x</sub>Cd<sub>x</sub>Te", Bull. Amer. Phys. Soc. Series II 22, No. 3, 340 (March 1977).<sup>x</sup> Presented at the March, 1977 meeting of the American Physical Society. This paper was the result of scientific collaboration between Honeywell and MIT.

Paul W. Kruse, Paul Norton, and John F. Ready, "Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te Spin-Flip Raman Lasers", presented at Electro-Optics/Laser 78 Conference, Boston, Massachusetts, September 19-21, 1978.

Muhammad A. Khan, Paul W. Kruse, and John F. Ready, "Resonant Four-Photon Mixing in Hg<sub>0.77</sub>Cd<sub>0.23</sub>Te", presented at the 1978 Annual Meeting of the Optical Society of American, San Francisco, California, October 31 - November 3, 1978.

Paul W. Kruse, John F. Ready, and Muhammad A. Khan, "Nonlinear Optical Effects in Hg<sub>1-x</sub>Cd<sub>x</sub>Te", presented at the Second International Conference on Infrared Physics, ETH, Zurich, Switzerland, March 5-9, 1979.

P. W. Kruse and M. A. Khan, "Nonlinear Optical Effects in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ ", presented by invitation at 1979 Conference on Laser Engineering and Applications, Washington, D.C. May 30 - June 1, 1979.

Paul W. Kruse and John F. Ready, "Nonlinear Optical Effects in  $(\text{Hg},\text{Cd})\text{Te}$ ", presented at IRIS Detector Specialty Group Meeting, Minneapolis, Minnesota, June 12, 13, 1979.

T. N. Casselman and P. E. Petersen, "On the Dominant Auger Mechanism in P-Type  $(\text{Hg},\text{Cd})\text{Te}$ ", presented at IRIS Detector Specialty Group Meeting, Minneapolis, Minnesota, June 12, 13, 1979.

John F. Ready, Muhammad A. Khan, and Paul W. Kruse, "Third Order Nonlinear Susceptibility in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ ", 1979 Annual Meeting of the Optical Society of America, Rochester, New York, October 8-12, 1979.

P. W. Kruse, J. F. Ready, and M. A. Khan, "Infrared Generation by Nonlinear Optical Means", Fourth International Conference on Infrared and Millimeter Waves and Their Applications, Miami Beach, 10-15 December, 1979.

Paul W. Kruse, "Nonlinear Optical Effects in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ", presented to an audience of scientists and engineers at Jet Propulsion Laboratory, Pasadena, California, 14 August 1979.

Paul W. Kruse, "Nonlinear Optical Effects in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ", presented to scientists and engineers from U. S. Army Missile Research and Development Command, plus local sections of SPIE and OSA, Huntsville, Alabama, 27 November 1979.

M. A. Khan, J. F. Ready, and P. W. Kruse, "Optical Phase Conjugation in  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$ ", CLEOS/ICF 80, San Diego, 26-28 February 1980.

T. J. Moravec, P. Schmidt (Bell Labs) and E. Spencer (Bell Labs), "Carbon Thin Films with Diamondlike Properties", 1980 Annual Meeting of the American Ceramic Society, Chicago, 26-30 April, 1980.

J. F. Shanley (Honeywell EOC), T. N. Casselman, C. T. Flanagan (Honeywell EOC) and M. B. Reine (Honeywell EOC), "Elevated Temperature  $(\text{Hg},\text{Cd})\text{Te}$  Heterodyne Detectors", IRIS Detector Specialty Group Conference, Menlo Park, California, July, 1980.

T. N. Casselman, "Calculation of the Auger Lifetime in Degenerate n-Type  $(\text{Hg},\text{Cd})\text{Te}$ ", IRIS Detector Specialty Group Conference, Menlo Park, California, July 1980.

P. W. Kruse, "Optical Phase Conjugation by Four-Wave Mixing in (Hg,Cd)Te," seminar at Army Night Vision and Electro-Optics Laboratory, Fort Belvoir, Virginia, August 13, 1980.

T. J. Moravec and T. W. Orent, "Electron Spectroscopy of Ion Beam and Hydrocarbon Plasma Generated Diamondlike Carbon Films," 27th Annual Meeting of the American Vacuum Society, Detroit, October 14-17, 1980.

T. N. Casselman, "Calculations of the Lifetime in Narrow Bandgap Semiconductors," graduate student seminar, Brown University, November, 1980.

. F. Shanley (Honeywell EOC), T. N. Casselman, C. T. Flanagan (Honeywell EOC), and M. B. Reine (Honeywell EOC), "Predicted Performance for an n<sup>+</sup>-p-p<sup>+</sup>, 10-14  $\mu$ m, (Hg,Cd)Te Photodiode from 77°K to 200°K," International Electron Devices Meeting, Washington, D.C., December 1980.



It is intended to present the following spoken papers at scientific meetings after 31 December 1980, based upon research carried out during the period 1 January 1977 - 31 December 1980.

Paul W. Kruse, "Optical Phase Conjugation by Four-Wave Mixing in Mercury Cadmium Telluride", Huntsville Electro-Optical Section and Working Group, OSA and SPIE, January 6, 1981 (by invitation).

Paul W. Kruse, Muhammad A. Khan, and John F. Ready "Reflective and Forward Mode Optical Phase Conjugation in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ ", accepted for presentation at the International Conference on Excited States and Multiresonant Nonlinear Optical Processes in Solids, Aussois, France, 18-20 March, 1981.

Muhammad A. Khan, Paul W. Kruse, and R. L. H. Bennett, "Optical Phase Conjugation in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  in the Forward and Reflective Modes", submitted for presentation at CLEO 81, Washington, D.C., 10-12 June 1981.

T.N. Casselman, "Calculation of the Lifetime in Defect-Free, Degenerate, N-Type  $(\text{Hg},\text{Cd})\text{Te}$ ," submitted for presentation at the Narrow Bandgap Semiconductor Conference, Linz, Austria, September 1981.

## 5.2 Consultative and Advisory Functions

During the period 1 January 1977 - 31 December 1980 there were numerous interactions between investigators under the contract and others at laboratories and agencies. They include the following:

- Demonstrations of the spin-flip Raman laser equipment and/or discussions of the spin-flip Raman laser experiment were presented to selected Air Force personnel, including:

Dr. Emile Rutner, Air Force Materials Laboratory,  
on 6 June 1977

Mr. Robert Hickmott, Air Force Materials Laboratory,  
on 15 June 1977

Dr. Arthur H. Guenther, Chief Scientist, Air Force  
Weapons Laboratory, on 13 October 1977

- Paul Norton presented a talk entitled "Tunable Infrared Radiation from Spin-Flip Raman Lasers" to Dr. Donn G. Shankland and 50 faculty members and students of the Air Force Institute of Technology, Dayton, Ohio, on 15 September 1977. This visit was coordinated by Max Swerdlow.
- Paul Kruse and John Ready visited the National Magnet Laboratory and the Massachusetts Institute of Technology on 5 October 1977 and met with Prof. Peter Wolff, Dr. R. L. Aggarwal, Dr. Benjamin Lax, and Dr. Dirk Muehlner to discuss mutual interests and collaborative experiments in nonlinear optics and spin-flip Raman laser action in  $(\text{Hg,Cd})\text{Te}$ .
- Profs. John Bardeen, Paul Coleman, George Russell and Ed Jordan of the University of Illinois visited our laboratory on 1 July 1977 and were given a demonstration of the spin-flip Raman laser.
- Paul Kruse discussed joint interests in nonlinear optical effects with Professor Peter Wolff and Professor Dirk Muehlner at MIT on 9 August 1978.
- Jack Ready met with Professor Arto Nurmikko, Brown University, at the 10th International Quantum Electronics Conference, Atlanta, 29 May - 1 June, 1978, to discuss the studies concerning the  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  samples supplied by us to Professor Nurmikko.
- Jack Ready met with Dr. Albert Feldman, National Bureau of Standards, at the 10th Symposium on Optical Materials for High Power Lasers, Boulder, Colorado, 12-14 September 1978 to discuss with him the properties and experiments concerning the sample of  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  supplied by us to him.

- Paul Kruse, Jack Ready, Tom Casselman, and Tom Moravec met with Professor Robert Brebrick, Marquette University, during his visit to the Honeywell Corporate Technology Center on May 17, 1978 to discuss his activities and Honeywell activities under the AFOSR contracts.
- Tom Casselman visited Brown University on 4,5 May, 1978. While there he delivered two samples of  $Hg_{1-x}Cd_xTe$  to Professor Arto Nurmikko and discussed Auger recombination analyses and plans under Honeywell's and Professor Nurmikko's AFOSR contracts.
- Paul Petersen visited Professor Arto Nurmikko at Brown University in January, 1978 to discuss the AFOSR-supported Auger studies. A benefit of this visit was the hiring of Dr. Steven Jamison, a post-doctoral colleague of Professor Nurmikko's, by Honeywell to work at the Honeywell Corporate Material Sciences Center.
- Tom Moravec discussed experimental details and results of his carbon thin films effort with three Air Force individuals who visited Honeywell on 15 November 1978, including MAJ James Stapp (Air Force Weapons Laboratory), Dr. Edward Kuhl (Air Force Materials Laboratory) and Dr. Alan Hopkins (Air Force Materials Laboratory).
- Tom Moravec visited P. Schmidt and F. Spencer of Bell Laboratories on 7 November 1978 to discuss carbon ion beam sources.
- Tom Moravec sent a copy of Honeywell's automated laser absorption calorimetry program to Dr. Susan Allen of the University of Southern California for use in an AFOSR contract on materials for high power lasers.
- Dr. Muhammad Asif Khan, who worked on the contract at Honeywell during the summer of 1978 while a graduate student on leave from MIT, joined Honeywell as a full-time employee and was assigned to work on the contract in May, 1979. He received his Ph.D. in physics from MIT in June, 1979. His thesis at MIT on the subject of nonlinear optics included four-photon mixing in  $(Hg,Cd)Te$  using Honeywell material. His presence at Honeywell helped strengthen the established relationship between the AFOSR contract investigators at Honeywell and MIT (Prof. Peter Wolff, Prof. Dirk Muehlner, Dr. Roshan Aggarwal).

- . Prof. Roshan L. Aggarwal, Assistant Director of the Francis Bitter National Magnet Laboratory, MIT, spent the period 17 July - 23 July 1979 with Honeywell carrying out collaborative spin-flip Raman laser investigations. Using  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  cavities supplied by Honeywell, he has previously studied their output as a function of input power, wavelength, and magnetic field using a TEA  $\text{CO}_2$  pump laser and Bitter magnet at the National Magnet Laboratory. While with Honeywell in July he carried out similar experiments using our Q-switched pump  $\text{CO}_2$  laser and electromagnet. The aim of these studies has been to resolve certain differences relating to data interpretation which have arisen because of the differing experimental approaches. Prof. Aggarwal's investigations at Honeywell were carried out at no cost to AFOSR.
- . M.A. Khan spent the period from 15 September through 4 October 1979 at MIT working in collaboration with C. Kash and Prof. Peter Wolff, on resonant four-wave mixing using Honeywell samples of  $\text{Hg}_{0.77}\text{Cd}_{0.23}\text{Te}$  and an MIT superconducting solenoid. The experiments were carried out in the Physics Department. Initial attempts to observe far infrared generation by difference frequency mixing failed due to lack of sensitivity of the detection apparatus. The experiments will be resumed during 1981. The visit to MIT by M.A. Khan was carried out at no cost to AFOSR.
- . T.N. Casselman visited Prof. A. Nurmikko at Brown University on 27 September 1979 to discuss Auger recombination in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ .
- . T.J. Moravec collaborated with AFOSR contractor Prof. G. LaPeyre of Montana State University in experiments involving use of ultraviolet photoemission to evaluate carbon thin films. Prof. LaPeyre visited Honeywell on 13 November 1978. Experiments were carried out at the University of Wisconsin synchrotron facility.
- . T.N. Casselman visited the Honeywell Electro-Optics Center, Lexington, Massachusetts to discuss the impact of degenerate lifetime calculations on the performance of  $(\text{Hg},\text{Cd})\text{Te}$  n+-p-p+ photodiodes responding in the 10-14  $\mu\text{m}$  spectral interval. He also provided advice on experiments using a new technique to measure lifetime and the intervalence band optical absorption coefficient.
- . T.J. Moravec described methods of producing carbon thin films to Dr. Stan Dometz of NASA-Lewis during the latter's visit to Honeywell on 10 June 1980. Dr. Moravec provided seven ion beam deposited carbon thin films to Dr. Dometz.

- T.J. Moravec reviewed carbon thin film research at Honeywell with Dr. Arthur Guenther, Chief Scientist, Air Force Weapons Laboratory, on Dr. Guenther's visit to Honeywell 28 August 1980.
- T.J. Moravec reviewed carbon thin film research at Honeywell with Dr. Allen Hopkins, Air Force Materials Laboratory, during Dr. Hopkin's visit to Honeywell on 21 October 1980.
- Paul Kruse presented a seminar "Optical Phase Conjugation by Four-Wave Mixing in (Hg,Cd)Te" at Army Night Vision and Electro-Optics Laboratory; Fort Belvoir, Virginia on 13 August 1980.
- Prof. Arto Nurmikko, an AFOSR contractor from Brown University visited the Honeywell Corporate Technology Center in October, 1980, to discuss with Tom Casselman measurements of lifetime in highly degenerate (Hg,Cd)Te.
- Tom Casselman visited Prof. Roshan Aggarwal, an AFOSR contractor at MIT, in November, 1980, to discuss long wavelength optical properties of (HgCd)Te.
- Tom Casselman visited Brown University in November, 1980, to discuss with Prof. Arto Nurmikko, an AFOSR contractor, a comparison of measurement and theory of lifetime in (HgCd)Te. He also met with Prof. Jan Tauc to discuss measurements of quantum efficiency in narrow bandgap semiconductors. Mr. Casselman also presented a seminar to graduate students concerning calculations of lifetime in narrow bandgap semiconductors.

### 5.3 Other Interactions

During the period 1 January 1977 - 31 December 1980, ten samples of  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  have been supplied to six scientific laboratories. The samples and recipients are listed below:

- Professor Arto Nurmikko, Brown University,  
Section 36-41, crystal 30577  
Section 50-51, crystal 30577  
Section 123-128, crystal 20275  
Section 129-134, crystal 20275  
Sample of  $x = 0.20$  material supplied by  
Honeywell Electro-Optics Center,  
transmitted by us.
- Professor Peter Wolff, Professor Dirk Muehlner,  
Massachusetts Institute of Technology  
Section 111-115, crystal 20275
- Dr. Roshan L. Aggarwal, National Magnet Laboratory  
Section 106-110, crystal 20275
- Dr. Carl Pidgeon, Department of Physics, Heriot-Watt  
University, Edinburgh, Scotland  
Section 35-39, crystal 20177
- Dr. Albert Feldman, National Bureau of Standards  
Section 42-65, crystal 20177  
  
We also supplied Dr. Feldman with one sample of  
 $\text{LiF}$  and one of  $\text{CaF}_2$ .
- Dr. E. Gornik, Ludwig Boltzman Institut fur  
Festkoperphysik, Vienna, Austria  
Section 129-134, less 2 mm, crystal 20275

In addition, seven ion beam deposited carbon thin films have been supplied to Dr. Stan Dometz of NASA-Lewis.

6. NEW DISCOVERIES, INTENTIONS, OR PATENT DISCLOSURES

During the period from 1 January 1977 - 31 December 1980, Honeywell has reported the following "firsts":

- First report of conversion efficiency, pulse shape, and spontaneous linewidth of a (Hg,Cd)Te spin-flip Raman laser
- First report of resonant four-photon mixing in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$
- First report of resonant six-photon mixing in any solid
- First report of noncollinear phase-matched resonant four-photon mixing in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$
- First report of resonant and nonresonant third order susceptibilities in (Hg,Cd)Te
- First report of optical phase conjugation in (Hg,Cd)Te
- First report of optical phase conjugation by conduction band nonparabolicity in any material
- First determination of the role of the Auger 7 recombination mechanism in (Hg,Cd)Te.
- First report that the predicted lifetime in strongly degenerate n-type (Hg,Cd)Te depends inversely upon the electron concentration
- First report that the residual background of hydrogen gas is necessary for production of carbon films in ultrahigh vacuum.

A patent disclosure "Determination of Chemical Composition of Alloy Semiconductors by 4-Photon Mixing," by P.W. Kruse, J.F. Ready, and M.A. Khan, has been filed with the U.S. Patent Office.

A patent disclosure "Dual Beam Technique for Carbon Film Deposition", by T.J. Moravec is in preparation.